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Fabry-Perot Survey of Emission-Line Galaxies

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Abstract. The recent results from a deep Fabry-Perot survey of nearby active and star-forming galaxies are presented. Line-emitting material is detected over two orders of magnitude in galactocentric radius, from the 100-pc scale of the active or starbursting nucleus out to several 10s of kpc, sometimes well beyond the optical confines of the host galaxies. The excitation and dynamical properties of the nuclear gas are studied to constrain the impact of galactic winds on the host galaxies and their environment. The properties of the warm ionized material on the outskirts of galaxies provide important clues for understanding galaxy formation and evolution. A new technique to search for starburst-driven wind galaxy candidates is discussed. The next generation of Fabry-Perot instruments on large telescopes promises to improve the sensitivity of emission-line galaxy surveys at least tenfold.

1. Introduction

The Fabry-Perot interferometer has the distinct advantage of providing detailed spectrophotometric information over a larger field of view (FOV) than that of other 3D instruments. The Fabry-Perot interferometer is therefore ideally suited to study nearby galaxies where the line-emitting gas extends over several arcminutes. This ionized material is an excellent probe of the phenomena taking place in the core of starburst and active galaxies, and can be used to quantify the impact of nuclear and star-formation activity on the environment and vice-versa.

Over the last decade, our group has used the scanning mode of the Hawaii Imaging Fabry-Perot Interferometer (HIFI) on the CFHT 3.6m and UH 2.2m and the TAURUS-II system on the AAT 3.9m and WHT 4.2m to study in detail a sample of about twenty nearby starbursts and active galaxies. A summary of the results from this portion of the survey is presented in §2. More recently, we have used a low-order Fabry-Perot interferometer to obtain very deep emission-line maps of several normal and active galaxies. This tunable-filter mode is particularly efficient to search for warm ionized gas on the outskirts of galaxies. The first results from this work are discussed in §3. The tunable filter has also proven to be an efficient tool to search for starburst galaxies with large-scale galactic winds. This technique was used recently to uncover a shock-excited wind in the starburst galaxy NGC 1482. The data are described in §4 along with possible applications of this technique to search for wind candidates at

higher redshifts. Future avenues of research with Fabry-Perot interferometers are briefly discussed in §5.

2. Superwind Survey with a scanning Fabry-Perot Interferometer

The initial portion of our galaxy survey focussed on obtaining high-quality data cubes of starburst and active galaxies with known galactic-scale outflows. All of the objects in the sample are nearby ($z < 0.01$) to provide a good spatial scale ($< 200 \text{ pc arcsec}^{-1}$), and present line-emitting regions which extends $> 30''$ to fully exploit the large FOV advantage of the Fabry-Perot interferometer. The Fabry-Perot data were combined with radio and X-ray data and HST images to track the energy flow through various gas phases (neutral, warm, hot, and relativistic). The high level of sophistication of recent hydrodynamical simulations (e.g., Strickland & Stevens 2000) has provided the theoretical basis to interpret our data and to predict the evolution and eventual resting place (disk, halo, or intergalactic medium) of the outflowing material. So far, high-quality data sets have been obtained and analyzed for about twenty galaxies (see recent review by Veilleux et al. 2001). These outflows typically show the following optical properties (see examples in Figs. 1 and 2):

Figure 1. Starburst-driven wind in NGC 3079. $\text{H}\alpha + [\text{N II}]$ line emission map of the nuclear superbubble obtained with HST WFPC2 by Cecil et al. (2001a). The superbubble is made of four separate bundles of ionized filaments, curving up to $\sim 0.6 \text{ kpc}$ above the disk, then dispersing as a spray of droplets. A Fabry-Perot data cube of the same region provides detailed kinematic information on the line-emitting gas (Veilleux et al. 1994). A remarkably good agreement is found between these data and the predictions of numerical simulations, including the presence of material with large vortex velocities near the top of the bubble indicative of a partially ruptured structure.

- The optical winds in starburst galaxies are always nearly perpendicular to the disk of the host galaxy (e.g., M 82, NGC 3079; Shopbell & Bland-Hawthorn 1998; Veilleux et al. 1994; Cecil et al. 2001a; Fig. 1), while AGN-driven optical winds are often lopsided and sometimes tilted with respect to the polar axis of the host galaxy (e.g., NGC 4388; Veilleux et al. 1999; Fig. 2).
- The solid angle subtended by these winds, $\Omega_W/4\pi \approx 0.1 - 0.5$.
- The radial extent of the line-emitting material involved in the outflow, $R_W = 1 - 5$ kpc.
- The outflow velocity of the line-emitting material, $V_W = 100 - 1500$ km s⁻¹ regardless of the escape velocity of the host galaxy. Until recently the record holder was NGC 3079, where outflow velocities in excess of 1500 km s⁻¹ are directly measured (Veilleux et al. 1994). But the outflow velocities in NGC 1068 are now known to be far larger than this value (Cecil et al. 2001b).
- The dynamical time scale, $t_{\text{dyn}} \approx R_W/V_W = 10^6 - 10^7$ years.
- The ionized mass involved in the outflow, $M = 10^5 - 10^7 M_\odot$, a relatively small fraction of the total ISM in the host galaxy.
- The ionized mass outflow rate, $dM/dt \approx M/t_{\text{dyn}} = 0.1 - 1 M_\odot \text{ yr}^{-1}$ (i.e. much larger than the mass accretion rate in AGN, or roughly equal to within a factor of 10 to the star formation rate in starburst galaxies).
- The kinetic energy of the outflowing ionized material, $E_{\text{kin}} = 10^{53} - 10^{55}$ ergs, taking into account both the bulk and “turbulent” (spectrally unresolved) motions. This mechanical energy is equivalent to that of $\sim 10^2 - 10^4$ Type II SNe.
- The kinetic energy rate of the outflowing ionized material, $dE_{\text{kin}}/dt \approx E_{\text{kin}}/t_{\text{dyn}} = \text{few} \times 10^{39} - 10^{42}$ ergs s⁻¹.
- Evidence for entrainment of (rotating) disk material is seen in several objects (e.g., Circinus, NGC 2992; Veilleux & Bland-Hawthorn 1997; Veilleux, Shopbell, & Miller 2001).
- The source of ionization of the line-emitting material taking part in these outflows is diverse. Pure photoionization by the AGN can explain the emission-line ratios in NGC 3516 (Veilleux, Tully, & Bland-Hawthorn 1995) and NGC 4388 (Veilleux et al. 1999). Shock ionization is probably contributing in Circinus and NGC 2992. Shock ionization often appears to be the dominant process in starburst-driven winds (see §4).
- Galactic winds in AGNs are roughly aligned with galaxy-scale (several kpc) radio emission, sometimes encompassing what appears to be poorly collimated radio “jets” (e.g., NGC 4388; Fig. 2; Veilleux et al. 1999). These mass-loaded “jets” are the probable driving engine for these winds. In most cases, however, torus-driven winds cannot formally be ruled out (Veilleux et al. 2001).

Figure 2. AGN-driven wind in NGC 4388. Barycentric velocity field of the line-emitting gas. (top) $H\alpha$; (bottom) $[O\ III] \lambda 5007$. North is at the top and east to the left. The optical continuum nucleus is indicated in each panel by a cross. The velocities range from about -200 km s^{-1} to $+200\text{ km s}^{-1}$ relative to systemic ($= 2,525\text{ km s}^{-1}$). The galactic disk is oriented in the east-west direction and shows bar streaming near the center in addition to circular rotation in the outer portions of the disk. The material above the disk does not follow normal galactic rotation; it is outflowing from the nucleus. A redshifted cloud located 2 kpc to the southwest of the nucleus is also taking part in the outflow. Loosely collimated radio “jets” are at the origin of this bipolar outflow (see Veilleux et al. 1999 for more detail).

- The excellent agreement between the predictions of numerical simulations and our data, both in terms of morphology and kinematics, confirms that the pressure gradient in the gaseous disk of the host galaxy is the primary focussing mechanism in starburst-driven winds.
- Some of these galactic winds appear to have a strong impact on the thermal and chemical evolution of the host galaxy and even possibly beyond (e.g., NGC 3079; Veilleux et al. 1994; Cecil et al. 2001a).

3. New Tunable-Filter Survey of Active and Star-Forming Galaxies

The optical data obtained during the early stage of the survey were obtained with conventional high-order Fabry-Perot interferometers used in a scanning mode, where the etalon is scanned over a range of spacings to build up a spectral data cube (x, y, λ) over a narrow spectral interval ($\sim 25 - 50 \text{ \AA}$). This technique provides complete spatial and kinematic sampling of the superwinds, an important condition to reconstruct their tridimensional structure. However, an important limitation of this technique is the relatively small effective FOV of the Fabry-Perot data, which is determined primarily by the range in gap spacings covered by our data cubes rather than the FOV of the instrument. Our data cubes typically contain only 30 – 50 images (limited by the time spent on each object) and therefore cover only about $\pm 1'$ ($\pm \sim 3 \text{ kpc}$) above and below the galaxy plane of our targets. Emission beyond this region falls outside the velocity range of our Fabry-Perot data and remains undetected.

Low-order etalons such as those used in the Taurus Tunable Filter (TTF; see Bland-Hawthorn & Jones 1998) can remedy the situation, providing gains of about an order of magnitude in both the effective FOV ($\sim 10'$ in *one* exposure) and $H\alpha$ limiting surface brightness ($\sim \text{a few} \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ *i.e.* about an order of magnitude fainter than that of published data on emission-line galaxies). For the past two years, our group has used the TTF on the AAT and WHT to map several active and starburst galaxies as well as a number of normal (“quiescent”) edge-on disk systems. The portion of the survey on normal galaxies is part of a Ph.D. thesis by University of Maryland student Scott T. Miller. The results so far can be summarized as follows (see review by Veilleux 2001; see also Fig. 3):

- In active and starburst galaxies, ionized filaments often extend out to several tens of kpc, sometimes beyond the H I edge of the host galaxy.
- Filamentary complexes are seen extending a few kpc above and below the disks of normal star-forming galaxies. Both the mass and extent of the extraplanar material in these galaxies appear to be correlated with the *local* surface density of star formation activity in the disk.
- Emission-line ratio maps constructed from multi-line imaging of these objects reveal line ratios which are not H II region-like. An early analysis of our results on normal disk galaxies combined with complementary long-slit spectra suggests that the extraplanar gas is primarily photoionized by the highly diluted and filtered radiation from OB stars in the disk (Miller

2002). However, an additional source of ionization is often needed to reproduce all of the vertical line ratio profiles. In active galaxies, the primary source of ionization of the extended nebula is either the AGN itself or shock excitation.

- Multi-line imaging slightly shifted in velocity space provides strong constraints on the kinematics of the warm ionized gas. In all cases studied so far, the gas appears to be bound to the host galaxy.

4. Search for Starburst-Driven Winds with the Tunable Filter

4.1. Discovery of a Galactic Wind in the Starburst Galaxy NGC 1482

In the course of our TTF survey of emission-line galaxies, we discovered a remarkable emission-line structure in the early-type spiral galaxy NGC 1482 (Veilleux & Rupke 2002). The TTF data are shown in Figure 3*d* and in more detail in Figure 4. Strong H α and [N II] emission is detected along the plane of the host galaxy (P.A. $\approx 103^\circ$). In addition, an hourglass-shaped structure is seen in both H α and [N II] $\lambda 6583$, extending along the minor axis of the galaxy at least ~ 1.5 kpc above and below the galactic plane. This structure is more easily visible in [N II] $\lambda 6583$ than in H α . This is particularly apparent in the lower left panel of Figure 4, where we present a [N II]/H α ratio map of this object. The [N II] $\lambda 6583$ /H α ratios measured in the disk of the galaxy [≈ 0.3 (outer disk) – 0.6 (inner disk)] are typical of photoionization by stars in H II regions, but the ratios in the hourglass structure are 3 – 7 times larger ([N II] $\lambda 6583$ /H $\alpha \approx 1.0 - 2.3$). This ratio of a collisionally excited line to a recombination line is fundamentally a measure of the relative importance of heating and ionization (e.g., Osterbrock 1989). The most likely explanation for these unusual line ratios is shock ionization resulting from the interaction of an energetic large-scale outflow with the ambient material of the host galaxy.

Complementary long-slit spectra obtained with the dual-beam spectrograph (DBS) on the MSSSO 2.3m telescope confirm that the hourglass structure is due to a large-scale galactic wind and that the extreme line ratios are produced through shocks (Fig. 5). Line splitting of up to ~ 250 km s $^{-1}$ is detected along the axis of the hourglass structure out to at least $16''$ (1.5 kpc) above and below the galaxy disk. Normal galactic rotation dominates the kinematics of the gas within $5 - 6''$ (~ 500 pc) from the disk. Maximum line splitting often coincides with regions of low emission-line surface brightness. These results can be explained if the extraplanar emission-line material forms a biconical edge-brightened structure which is undergoing outward motion away from the central disk. In this case, the blueshifted (redshifted) emission-line component corresponds to the front (back) surface of the bicone. The lack of obvious velocity gradient in the centroid of the line emission suggests that the main axis of the bicone lies close to the plane of the sky. The fact that the amplitude of the line splitting does not decrease significantly with distance from the galaxy indicates that the entrained material is not experiencing significant deceleration (i.e., it is a blown-out wind). A lower limit of 2×10^{53} ergs is derived for the kinetic energy of the outflow based on the deprojected gas kinematics and the amount of ionized material entrained in the outflow. We find that the starburst at the

Figure 3. Tunable filter images of nearby galaxies. North is up, east to the left. **(a)** One-hour $H\alpha$ image of the archetypical Seyfert 2 galaxy NGC 1068. Line emission is detected for the first time out to ~ 12 kpc from the nucleus, slightly beyond the H I edge of this galaxy. The biconical geometry of the complex and the relative strengths of the emission lines suggest that the central AGN is contributing to the ionization of this material. (Shopbell, Bland-Hawthorn, & Veilleux 2002, in prep.); **(b)** A line-emitting filament is detected at 19 kpc from the nucleus of NGC 7213. This filament was independently discovered by Hameed et al. (2001), and seems to coincide spatially and kinematically with tidal debris seen in H I 21 cm. (Veilleux & Rupke 2002, in prep.); **(c)** $H\alpha$ of the field surrounding the quasar MR 2251–178. A spiral-like nebula extending ~ 200 kpc around the quasar is detected in this image. This nebula is ionized by the quasar and in rotation around it (see Shopbell, Veilleux, & Bland-Hawthorn 1999 for more detail). **(d)** [N II] $\lambda 6583/H\alpha$ ratio in the starburst galaxy NGC 1482. The [N II]/ $H\alpha$ ratio is < 1 in the galactic disk ($PA = 100^\circ$) but > 1 in the material above the disk. These data suggest the presence of a shock-excited superwind in NGC 1482. See §4 and Veilleux & Rupke (2002) for more detail.

Figure 4. Narrow-band images of NGC 1482 obtained with the TTF: (clockwise from upper left corner) red continuum, [N II] $\lambda 6583$ line emission, $H\alpha$ line emission, and [N II] $\lambda 6583/H\alpha$ ratio. The panels on the right are on a logarithmic intensity scale, while those on the left are on a linear scale. North is at the top and east to the left. The positions of the continuum peaks are indicated in each image by two crosses. The spatial scale, indicated by a horizontal bar at the bottom of the red continuum image, is the same for each image and corresponds to $\sim 21''$, or 2 kpc for the adopted distance of 19.6 Mpc for NGC 1482. The [N II] $\lambda 6583/H\alpha$ ratio is below unity in the galaxy disk but larger than unity in the hourglass-shaped nebula above and below the disk. This structure is highly suggestive of a galactic wind.

Figure 5. Sky-subtracted long-slit spectra obtained parallel to the galactic disk (P.A. $\sim 103^\circ$). For each panel, south-east is to the left and north-west to the right. The spectra displayed on the left are offset to the north-east by $0''$ (bottom panel), $9'' - 10''$, $11'' - 12''$, and $13 - 14''$ (top panel) from the major axis of the host galaxy. The spectra displayed on the right are offset by approximately the same quantity in the south-west direction. The vertical segment in each panel represents 500 km s^{-1} . The presence of line splitting above and below the disk confirms the presence of a large-scale wind in this galaxy.

base of the wind nebula is powerful enough to drive the outflow, based on the star formation rate derived from the *IRAS* database. A more detailed discussion of the TTF data may be found in Veilleux & Rupke (2002).

4.2. On the Use of Excitation Maps to Identify Starburst-Driven Wind Galaxies

The traditional method of identifying galaxy-scale winds in starburst galaxies is to look for the kinematic signature (e.g., line splitting) of the wind along the minor axis of the host galaxy disk. Edge-on disk orientation reduces contamination of the wind emission by the underlying disk material and facilitates the identification. This method is time-consuming since it requires deep spectroscopy of each candidate wind galaxy with spectral resolution of $\lesssim 100 \text{ km s}^{-1}$. Line ratio maps like the ones shown in Figures 3d and 4 represent a promising new way to detect galactic winds in starburst galaxies. The line ratio method only requires taking narrow-band images of candidate wind galaxies centered on two (or more) key diagnostic emission lines which emphasize the contrast in the excitation properties between the shocked wind material and the star-forming disk of the host galaxy. $[\text{N II}] \lambda 6583/\text{H}\alpha$, $[\text{S II}] \lambda\lambda 6716, 6731/\text{H}\alpha$, and $[\text{O I}] \lambda 6300/\text{H}\alpha$ are the optical line ratios of choice for $z \lesssim 0.5$ galaxies (these ratios are enhanced in the wind of NGC 1482), while $[\text{O II}] \lambda 3727/\text{H}\beta$ and $[\text{O II}] \lambda 3727/[\text{O III}] \lambda 5007$ could be used for objects at larger redshifts. The spatial resolution of these images must be sufficient to distinguish the galaxy disk from the wind material. Using NGC 1482 as a template, we find that high- $[\text{N II}]/\text{H}\alpha$ winds in edge-on starburst galaxies would still be easily detected out to a distance of $\sim 200 \text{ Mpc}$ under $1''$ resolution. Imagers equipped with adaptive optics systems should be able to extend the range of these searches by an order of magnitude.

This method relies on the dominance of shock excitation in the optical line-emitting wind component. Surveys of local powerful wind galaxies (e.g., Heckman, Armus, & Miley 1990; Bland-Hawthorn 1995; Veilleux et al. 1995; Lehnert & Heckman 1996; Veilleux 2001) confirm that shocks generally are the dominant source of excitation in the wind material. These shock-dominated wind nebulae present line ratios which are markedly different from the star-forming disks of the host galaxies. The superbubble in NGC 3079 presents large $[\text{N II}] \lambda 6583/\text{H}\alpha$ ratios, reaching values of ~ 3 at the base of the bubble where the widths of the emission lines exceed 400 km s^{-1} . This is another clear case of shock-excited wind triggered by a nuclear starburst. At the other end of the excitation spectrum is the wind in M 82. The $[\text{N II}]/\text{H}\alpha$ map of the southern wind lobe of M 82 (Fig. 4 of Shopbell & Bland-Hawthorn 1998) presents two distinct fan-like structures with H II region-like ratios originating from the two bright star-forming regions in the disk of this galaxy. The line ratio technique would not be able to distinguish between line emission from this type of photoionization-dominated wind nebulae and contamination from a star-forming disk seen nearly face-on. Blind searches for galactic winds based on the excitation contrast between the disk and wind components would therefore favor the detection of winds in edge-on hosts where the wind component is not projected onto the disk component. This orientation bias would need to be taken into account to get a complete census of starburst-driven wind galaxies.

AGN-driven winds may also contaminate samples selected from excitation maps if the spatial resolution is not sufficient to separate the active nucleus from the disk material.

5. Future

The contribution of J. Bland-Hawthorn to these proceedings lists large telescopes with planned or proposed Fabry-Perot interferometers. Tunable filters on 6 – 10m telescopes will be ideally suited to survey the line-emitting universe at low and high redshifts. This is particularly true for the Maryland-Magellan Tunable Filter (MMTF) proposed for the Magellan 6.5m telescope which will combine wide field of view (monochromatic spot with diameter $\sim 10' - 27'$) with outstanding narrow-band imaging capabilities over a broad range in wavelengths (5000 – 9200 Å) and bandpasses (10 – 100 Å). The exceptional areal coverage and sensitivity of this instrument will result in a gain of at least an order of magnitude in survey efficiency. MMTF will be a very efficient tool to study star formation over a broad range of redshifts and galaxy environments.

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